

XI. ALTERNATIVE FUELS

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Some potential problems related to the use of alternative aviation turbine fuels are discussed and both ongoing and required research into these fuels is described. Fuel consumption by domestic airlines has tripled during the first 15 years of commercial jet aviation (fig. XI-1). Most forecasts predict a reduced rate of growth for air transportation in the future. Nevertheless, the rate of increase in demand for aviation turbine fuels is expected to exceed that for automotive gasoline. Forecasts of the growth rate in fuel consumption by domestic airlines vary from 4 to 7 percent. Even the conservative prediction means a doubling of the fuel required for air transportation by the year 2000.

Presently, jet aircraft are totally dependent on petroleum-derived kerosene fuels. At some time in the future, it will be necessary to obtain aviation fuels from sources other than petroleum. Domestically, these alternative sources include oil shale and coal. The relative reserves of petroleum, oil shale, and coal estimated from Department of the Interior statistics (ref. 1) are illustrated in figure XI-2. Estimates of fossil fuel reserves from other sources may differ in terms of the absolute magnitude of these reserves, but the relative ranking of these fossil fuels resources is in agreement with other studies. Based on the current total energy use rate, these estimates predict that domestic petroleum reserves will be nearly depleted around the turn of the century. The reserves of oil shale and coal could supply our total energy needs for several hundred years.

Other alternative fuels, such as liquid hydrogen, are being studied within NASA, but this discussion is limited to aviation turbine fuels composed of liquid hydrocarbons. The consensus of both industry and government is that we will continue using conventional aviation turbine fuels for the foresee-

able future. It may be necessary, however, to use relaxed-specification hydrocarbon fuels for jet aircraft when these fuels are obtained from lower quality petroleum and, eventually, from alternative sources such as oil shale and coal. We anticipate that these lower quality fuels will have a lower proportion of hydrogen to carbon, a wider boiling range, a higher final boiling temperature, and larger concentrations of undesirable impurities. Therefore, it is important to prepare now for this eventuality by determining the problems to be expected in using these fuels in jet aircraft.

NASA has begun several research and technology programs concerned with the efficient utilization of fossil fuels for aviation. One of these efforts is a jet fuels technology program that is being conducted jointly by the Air Force Aero-Propulsion Laboratory and the NASA Lewis Research Center. This program is aimed at investigating the problems in using alternative sources of aircraft fuels, such as shale oil and coal syncrudes, in both commercial and military aircraft (refs. 2 and 3). Another program will examine an approach to minimizing refinery energy consumption, and thereby reducing fuel costs, by relaxing current aircraft fuel specifications. As a consequence, the effects of altered fuel properties on the performance and durability of engine components must be determined in order to evolve the technology required to use these fuels. The Air Force, Army, NASA, the Energy Research and Development Administration (ERDA), the Federal Aviation Administration (FAA), and other government agencies are also participating in a Navy-coordinated program that is investigating the feasibility of converting shale oil and coal syncrudes into military-grade fuels.

Another approach to fuels conservation is to improve aircraft energy efficiency. NASA has recently organized a program to minimize aircraft fuel usage by reducing specific fuel consumption, reducing engine weight, reducing aircraft weight, and improving aircraft aerodynamics (ref. 4). However, this area of the aeronautics research program is not covered by this paper.

POTENTIAL PROBLEMS FROM RELAXING JET FUEL SPECIFICATIONS

Figure XI-3 relates changes in current jet fuel property specifications to resulting problems. A higher final boiling point results in poorer ignition

characteristics. This could make starting an engine more difficult during cold weather and could lower the altitude ceiling at which the combustor could be relit in the event of a flameout. In addition, a higher final boiling point could increase carbon monoxide (CO) and total hydrocarbon (THC) emissions during idle or low-power operation.

Fuels with a greater concentration of aromatic compounds have chemical compositions with lower proportions of hydrogen to carbon since aromatics are hydrocarbon compounds having about half as much hydrogen as the other hydrocarbons in jet fuel. This results in increased smoke emissions and increased flame radiation, which in turn raises combustor liner temperatures.

A higher aromatic content may also bring about a poorer chemical or thermal stability and result in the formation of gums, varnish, or carbon within the heated parts of the fuel system. The same problem may result from an increase in the concentration of organic nitrogen compounds in the fuel. Furthermore, increasing the nitrogen content of the fuel will increase the nitric oxide (NO_x) emissions. Fuels with a higher freezing point would introduce a serious limit on fuel pumpability.

This paper discusses all these critical problems. Other problems may result from changes in fuel properties, such as the effect of alternative fuels on engine materials and seals, but these are not covered here.

PROPERTIES OF FUTURE AVIATION FUELS

The property changes charted in figure XI-3 can be discussed quantitatively with respect to the future aviation jet fuels. Figure XI-4 shows the boiling range of various petroleum products, about 100° to 650° F. Commercial jet aircraft fuel, Jet A, has a relatively narrow boiling range. The initial boiling point, a minimum of 330° F, is necessary to maintain the flashpoint above 100° F in order to reduce the probability of a fire during fueling or following an emergency landing. The final boiling point for Jet A is usually about 520° F to comply with limits on the freezing point. Figure XI-5 shows the increase in freezing point to be expected as the final boiling point is increased. The freezing point of a fuel blend is the temperature at which wax components in the fuel solidify, and figure XI-5 indicates that sizable increases in freezing point can occur with small increases in

final boiling point. To expand the jet fuel supply from petroleum in the future by increasing the proportion of total crude allotted to jet fuel production, this boiling range may be enlarged substantially. In addition, jet fuels derived from the alternative sources will probably have higher final boiling points than today's conventional Jet A.

Another property shown in figure XI-3, the aromatic content, has more than one effect. High aromatic content leads to smoky combustion, which in turn increases the heat radiation of the flame inside the combustor to the combustor walls. This can shorten the life of the combustor and other parts of the engine. Fuels with greater aromatic content also may have less chemical stability, resulting in breakdown with storage for long periods at ambient temperatures as well as with exposure to elevated temperatures in the fuel lines in the engines.

An aromatic compound is an unsaturated cyclic hydrocarbon, where the unsaturation refers to the hydrogen content. Three types of aromatic compounds are shown in figure XI-6: benzene; an alkylated benzene, ethyl benzene; and a two-ring compound, tetralin, with one ring partially saturated and one ring unsaturated. The hydrogen content of each is shown. For various reasons, it is suggested that jet fuel specifications be written in terms of hydrogen rather than aromatic content. Figure XI-7 illustrates that the aromatic content does not uniquely specify the hydrogen content, but hydrogen values do lie with a band. For Jet A, with a limit on aromatics of about 20 percent, the hydrogen content is about 14 percent.

For jet fuels from alternative sources, the specification limits for aromatic or hydrogen content may be difficult to achieve. This is shown by the comparison of crude oil hydrogen contents in figure XI-8. The maximum hydrogen contents for shale oil and coal syncrudes just approach the minimum for petroleum crude. A typical shale oil will have a hydrogen content between 10.5 and 11 percent. A typical coal syncrude might be lower in hydrogen, ranging from 9.5 to 11 percent. The value found for the coal syncrude is, of course, dependent on the amount of processing that the original coal feed, with a hydrogen content of 4 to 5 percent, received.

Another property problem introduced by syncrude sources is nitrogen content. Shale oil is quite high in nitrogen. Organic nitrogen compounds are known to affect chemical stability and emissions to some extent, as is discussed later in this paper. Figure XI-9 illustrates that for shale oil, the

nitrogen content is typically between 1.4 and 2.2 percent, which is much higher than for coal, 0.1 to 0.8 percent, and for petroleum crude, 0.01 to 0.2 percent.

EFFECT OF RELAXING FUEL SPECIFICATIONS ON COMBUSTORS AND FUEL SYSTEMS

Combustor Performance

The changes in fuel properties discussed in the previous section can affect combustor performance. An increase in final boiling point can decrease volatility. This can reduce altitude relight capability and increase idle emissions although, based on the limited amount of data available to date, the effect is not large. Increases in aromatic content or, conversely, decreases in hydrogen content of the fuel, on the other hand, have a pronounced effect on smoke and on liner temperatures. Single-combustor tests have been conducted using prepared fuel blends with varying amounts of aromatics (ref. 5). The effect of the hydrogen content of the fuel on smoke is shown in figure XI-10. At both cruise and takeoff conditions, strong increases in exhaust smoke were observed as the hydrogen content of the fuel decreased. The effect of hydrogen content on maximum liner temperatures is shown in figure XI-11. As the aromatic content of the fuel increases and the hydrogen content decreases, the flames become more luminous and hence radiation to the liner increases. Sharp rises in maximum liner temperatures were observed as the hydrogen content of the fuel decreased. At cruise, liner temperatures for fuels in the Jet A range (13.5 to 14 percent hydrogen content) were well below 1600° F for all fuels. However, for fuels with hydrogen contents of 12 percent or below, severe liner durability problems could arise. At takeoff, maximum combustor liner temperatures exceeded 1600° F for all fuels, but the time spent at takeoff and hence the exposure time of the liner to these high temperatures is quite short.

Organic nitrogen compounds, or fuel-bound nitrogen, can cause increased NO_x exhaust emissions. This effect is shown (ref. 5) in figure XI-12 for two fuels: a standard petroleum-based Jet A with a nitrogen content of less

than 0.001 percent by weight (10 ppm) and oil-shale-derived Jet A with a nitrogen content of about 0.08 percent by weight (800 ppm). The NO_x values shown for the petroleum-based fuel are primarily thermal NO_x , that is, the result of high-temperature oxidation of the nitrogen in the combustion air. The increase in NO_x exhibited by the oil-shale-derived Jet A is the result of nitrogen in the fuel being converted to NO_x . Although the increase does not seem large on a percentage basis, the fact that the proposed NO_x emissions standards are extremely difficult to achieve even with nitrogen-free fuel makes the fuel-bound nitrogen a serious additional problem.

Thermal Stability

The fuel-bound nitrogen and the increased aromatic content of alternative fuels introduces another problem, thermal stability. Figure XI-13 shows tubes that have been heated to various temperatures with fuel flowing over the outside of them. They might represent the tubes in a fuel-oil heat exchanger, for example. The photograph illustrates what can occur with turbine fuels that are not thermally stable at the temperatures the fuels will encounter on their way through the fuel system to the combustor. The three tubes at the left were exposed to fuel produced from a shale oil syncrude with a nitrogen content of 0.175 weight percent, at the temperatures shown. The two tubes at the right were exposed to syncrude fuel with 0.015 weight-percent nitrogen.

One can readily note from figure XI-13 that (1) as the temperature of the tube increases, the amount of fuel breakdown material deposited is much greater; and (2) at similar temperature levels, the fuel with the higher nitrogen content shows much heavier deposits.

Freezing Point

Figure XI-5 has illustrated the potential increase in fuel freezing point with relaxed final boiling point specifications. Fuel stored in aircraft tanks can reach very low temperatures during long flights. Figure XI-14 shows extreme fuel temperatures that may be encountered during a long-range flight. These data were calculated by the Boeing Company to show fuel tank

temperatures when the static temperature at altitude is as low as -98°F (ref. 6). This is an extreme case, with a one-day-a-year probability. Two curves are shown, each with a widely different initial ground-loading fuel temperature. The effect of the different initial temperatures on in-flight fuel temperatures decreases as the flight progresses. After a period of time, the in-flight fuel temperature is completely independent of the initial temperature. The fuel temperature eventually reaches a minimum value of -46°F , which is approximately the stagnation temperature at a cruise Mach number of 0.84 for the ambient static temperature. The rise in temperature at the end of the flight occurs because of increased altitude ambient temperature during that portion of the flight.

Jet fuel is a mixture of chemical compounds and does not have a fixed freezing point. Instead, it undergoes a large increase in viscosity and a partial phase change over a range of temperatures. Even this semisolid fluid can threaten operating problems. Figure XI-15 is a test-rig photograph, from the Boeing Company (ref. 7), of a pump inlet screen coated with gel-like freezing fuel. Fuel freezing has always been avoided by in-flight monitoring of fuel tank temperatures and use of jet fuels with low, conservative freezing-point specifications.

PROPOSED SOLUTIONS TO PROBLEMS OF ALTERNATIVE FUELS

Refining Jet Fuel to Current Specifications

One obvious solution to the problems addressed in the preceding sections would be to pay the price for the additional refining of alternative jet fuels to meet current specifications. Refining requirements will depend on the source of the crude. Jet fuels from petroleum crudes are produced in many instances by straight distillation (fig. XI-16). The products from the distillation are separated by boiling range, and adequate amounts of jet fuel are obtained. For other petroleum crudes, more costly hydrotreating processes are required, either for adding hydrogen to increase the saturated hydrocarbon content or for removing sulfur or nitrogen impurities. We can expect this refining treatment to increase as poorer quality petroleum crudes are used. Hydrotreatment will also be required for saturation and sulfur removal

with coal syncrudes and for nitrogen removal with oil shale crudes. In addition, experience has shown that the fraction of shale oil and coal syncrudes in the jet fuel boiling range is considerably less than that of typical petroleum crudes. For reasonable yields of jet fuels from these sources, hydrocracking, which will convert high-boiling-point material to material boiling in the jet fuel range, will certainly be required. Hydrocracking usually takes place in a two-stage reactor.

From work done under contract to NASA and the Air Force, the extent of some of the hydroprocessing required in making jet fuels from syncrudes has been determined (refs. 2, 3, and 8). One consideration is the increased amount of hydrogen that will be required above that usually needed in petroleum processing. Two specific cases are shown in figure XI-17. During shale oil processing, the hydrogen consumption is increased from 900 to 1100 standard cubic feet per barrel in reducing the nitrogen level from about 0.2 percent to 0.015 percent (2000 to 150 ppm). In coal syncrude processing, hydrogen content is the controlling factor and, in this case, an increase in hydrogen consumption from 600 to 1100 standard cubic feet per barrel is needed to increase hydrogen content from 12.5 percent to 13.5 percent.

One other important factor was noted in the studies performed (ref. 8). The catalyst deactivation in hydroprocessing was more rapid than that experienced with petroleum crudes under similar conditions. This is a problem that may cause additional complexity and expense in syncrude processing.

Control of Fuel Thermal Stability

The upgrading of alternative fuels by improved refinery processing is one approach to solving the problem of reduced thermal stability. Changes in fuel system design is another approach. For an understanding of these solutions, it is helpful to look at some basic studies of fuel thermal stability (ref. 9).

Aircraft turbine fuels must be stable at the temperatures they will encounter in the fuel system. Practically, this means there must be no gum or deposits built up on heated surfaces such as heat exchanger tubes or manifold piping and no cracking or particulate formation that might clog small passageways in the fuel system such as filters or fuel nozzles.

The laboratory tests that have been developed to check on this particular fuel behavior subject the fuel to a thermal stress in a test rig such as that shown schematically in figure XI-18. A small tube is heated electrically to the test temperature. The fuel flows up through an annulus surrounding this heated surface and out through a test filter. During this procedure, any tendency of the fuel to form particulates large enough to block this test filter can be noted by a buildup of pressure drop across the filter. At the same time, deposits may also form on the heated tube. These were illustrated previously in figure XI-13.

Any chemical changes bringing about the fuel instabilities should occur at an increased rate as the fuel temperature is increased. In general, either the pressure drop across this test filter builds up at a faster rate or the indicated deposits on the tube build up at a faster rate, as the test temperature is increased. Thus, one way of comparing the thermal stabilities of fuels is to determine the maximum temperature of the heated fuel before the test exceeds certain specified limits of pressure drop or tube deposit buildup. This temperature is then referred to as the "breakpoint temperature." For the shale- and coal-derived fuel data shown here, it was the tube deposits rather than the filter pressure drop that exceeded the specified limit first and so determined the breakpoint temperature.

Figure XI-19 illustrates the determination of the breakpoint temperature. A tube deposit rating number (TDR), which is obtained with a light reflectance device, is shown as a function of the test temperature for two shale-derived fuels. The TDR number is an arbitrary scale, zero being a clean tube and 50 representing a dark, comparatively heavy deposit. When the temperature range at which deposits start to occur is reached, the amount of the deposit increases rapidly with temperature. The breakpoint for the fuel is defined as the temperature at which the tube deposit rating passes through some level selected to define the "pass-fail" condition. A value of 13, illustrated by the dashed line in figure XI-19, is used for the fuel comparisons presented here. Currently, Jet A is expected to pass this test at 500° F. The breakpoint temperatures of the two shale fuels, 420° and 460° F, would not meet the current jet fuel requirement.

Breakpoint temperatures for a number of shale- and coal-derived fuels were determined by this procedure and are shown in figures XI-20 and -21. Figure XI-20 shows the breakpoint temperatures as a function of the weight

percentage of fuel-bound nitrogen for shale-derived fuels. This figure contains both NASA data and data obtained at the Exxon Research and Engineering Laboratory on an Air Force contract (refs. 3 and 9). It indicates that the shale-derived fuels that were hydrotreated to remove nitrogen down to only 0.1 to 0.2 weight percent had breakpoint temperatures below 450° F. The fuels hydrotreated more severely, to nitrogen contents of about 0.01 to 0.02 weight percent (100 to 200 ppm), had breakpoints in the 450° to 500° F range. For breakpoints of 500° F or more, it appears that the fuel will have to be hydrogenated to achieve nitrogen contents below about 0.01 percent (100 ppm).

Although it is known that fuel-bound nitrogen is a factor contributing to the instability of fuels, it is not possible to determine if it is solely responsible for the stability differences. In the preparation of these fuels, the nitrogen content of the product was monitored in establishing the severity of the hydrotreatment used.

Figure XI-21 shows the breakpoint temperature for some coal-derived fuels as a function of the weight percentage of hydrogen. More severe hydrotreatment was required for these fuels than for the shale-derived fuels. The fuel-bound nitrogen in all the coal-derived fuels was equal to or less than 6 ppm. The hydrogen content of the fuel was monitored as an indication of the severity of treatment. In this case, a general trend was to higher breakpoint temperatures as the weight percentage of hydrogen was increased, a 500° F breakpoint generally requiring at least 13-percent hydrogen. Typical Jet A hydrogen content would be around 13.5 to 14 percent, and the breakpoint must be at least 500° F.

Problems related to extending the final boiling point of jet fuels have also been discussed. Figure XI-22 shows the decreasing trend that thermal breakpoint follows for fuels from two different syncrudes as the final boiling point of the fuels is increased.

Figures XI-20 to -22 present some of the early stability data available on turbine fuels from synthetic sources and indicate the general severity of the refining processing that would be required to produce synthetic fuels with stabilities comparable to current jet fuels. Hydrotreatment, of course, is not the only possible approach to solving the thermal stability problem. It may be that modifications can be made to the fuel system design so that the fuel does not reach as high a temperature level. This would permit the use of fuels of lower thermal stability.

Combustor Technology for Use of Relaxed-Specification Fuels

Again, rather than refining the alternative-source fuel to meet current specifications, it may be possible to design jet aircraft engine combustors to handle off-specification fuels.

Results of tests reported in the section Combustor Performance (figs. XI-10 and -11) show that lowering the hydrogen content of jet fuels can cause problems with liner temperatures and smoke emissions for conventional combustors. In the Experimental Clean Combustor Program, discussed in previous papers at this conference, concepts have been evolved that promise not only lower exhaust emissions, but also reduced sensitivity to relaxed fuel specifications. Two of these concepts, the Vorbix combustor for the Pratt & Whitney JT9D engine and the double-annular combustor for the General Electric CF6-50 engine are shown for reference in figure XI-23. Both combustors feature staged combustion with a relatively rich zone for idle operation and a leaned-out main combustion zone for high-power operation.

Some of the results obtained with these combustors are shown in figure XI-24. Since the various data were not all obtained at the same combustor-inlet conditions, they are plotted as the difference between maximum liner temperature and combustor-inlet temperature. The data obtained with a production-model full-annular CF6-50 combustor and a single-can JT8D combustor exhibit the strong dependency of maximum liner temperature on the hydrogen content of the fuel. The data obtained with the experimental Vorbix and double-annular combustors show a relative insensitivity of maximum liner temperatures to the hydrogen content of the fuel.

Similar results can be expected with regard to exhaust smoke because of the leaned-out main combustion zones of the experimental combustors.

Another method of reducing liner temperatures consists of coating the inside of the combustor liner with a thermal-barrier coating. Shown in figure XI-25 is a JT8D combustor liner that was coated with a thermal-barrier coating developed at the Lewis Research Center for application to turbine blades. The coating consists of a bond coat of a nickel-chromium-aluminum-yttrium alloy covered with a ceramic layer of 12-percent-by-weight yttria-stabilized zirconia. To apply the coatings, it was necessary to cut the combustor lengthwise to accommodate the coating apparatus and

then to reweld the parts. Care was taken not to cover the cooling slots and holes.

The results obtained with Jet A fuel (ref. 10) are shown in figure XI-26. Maximum liner temperatures are plotted as a function of average exhaust-gas temperature. For both cruise and takeoff, substantial reductions in maximum liner temperatures were achieved. Although no endurance tests were made, no deterioration of the coating was observed after about 6 hours of cyclic operation including several startups and shutdowns.

With regard to increased NO_x emissions resulting from high concentrations of fuel-bound nitrogen in syncrude-derived fuels (fig. XI-12), no easy solution is in sight. To meet the rigid NO_x emission standards, either the fuel-bound nitrogen will have to be removed at the refinery at added expense or ways will have to be found to reduce emissions through redesign of the combustor. The approach to minimizing thermal NO_x suggested in other papers in this conference, namely, lean premixed combustion, does not reduce the conversion of fuel-bound nitrogen. Other approaches, such as rich combustion followed by a rapid transition to lean operation, suggested by the paper on emission control for ground power gas turbines, can introduce problems of excessive smoke formation resulting from the rich primary zones. Good experimental data on this design are not available to date.

Fuel System Technology for Use of High-Freezing-Point Fuels

Fuel system modifications, rather than combustor modifications, are the suggested solution for high-freezing-point problems. Fuels with higher freezing points than current specifications can be used if the fuel is heated in flight. Figure XI-27 shows several curves of predicted fuel temperatures during a long-range flight. The zero-heat-input curve repeats the in-flight temperature calculations shown in figure XI-14 and represents an extreme case expected one day a year, with a minimum fuel temperature of -46°F . The other two curves illustrate the fuel temperatures in flight with the fuel heated at the rates indicated. The minimum fuel temperature in flight can be raised to -20°F by heating the fuel at a rate of 3500 Btu/min for each engine - fuel tank combination. The minimum fuel temperature can be raised to 0°F by a heat input of 6200 Btu/min.

The calculated heating requirements can be reduced by insulating the fuel tanks. Figure XI-28 presents crossplots of the temperature calculations, indicating the required heat inputs as a function of the resulting minimum fuel temperature. Each curve represents the heating required with various thicknesses of glass-epoxy insulation. The decrease in heating requirements by using insulation can be sizable. For example, without insulation, 6200 Btu/min are required to maintain the fuel above 0° F. With a $\frac{1}{2}$ -inch thickness of insulation, the same minimum temperature can be maintained with 3900 Btu/min; with 1 inch of insulation, only 1900 Btu/min are required.

The Boeing Company under NASA contract (ref. 6) has completed a preliminary study of practical fuel heating systems based on the 747 airplane. Figure XI-29 is a cutaway drawing showing several possible heat source systems mounted on the wing fuel tanks and engines of the 747. Some existing components, with minor modifications, can be used as heat sources. Three examples are shown: the cabin airconditioning heat rejection, fuel recirculation from the fuel pump, and fuel recirculation from the engine lubricating oil heat exchanger. The latter two heating systems would be based on pumping fuel at a maximum rate at all times and then recirculating, or returning, the excess fuel flow back to the wing tank. The excess fuel would be heated by the pump work or lubricating oil heat rejection to warm the bulk of the tank fuel. An additional three systems, each capable of higher heating rates, are also shown. These involve major modifications. These systems include a tailpipe heat exchanger, an engine compressor air bleed heat exchanger, and an electrical heater powered by an engine-drive generator. Most likely, these systems would heat the fuel indirectly through a second heat exchanger loop, using an inert fluid. Wing tank insulation is also shown in figure XI-29.

Data on these fuel heating systems are compared in table XI-1. The first three systems are minor modifications of existing aircraft components, using heat sources ranging from 2000 to 4300 Btu/min. These rates could be increased by using combined systems at the risk of control complexity. Two columns in this table show predicted penalties for the heating systems in terms of airplane weight increase and fuel consumption expressed as a percentage of cruise fuel flow. These calculations are not yet quantitatively available for the minor modifications, but the penalties would be low. These

systems, for the most part, use existing heat rejection in the airplane and powerplants.

Table XI-1 also compares the major modifications, which involve greater weight and performance penalties but which promise future use with very high-freezing-point fuels. These systems are sized for 6200 Btu/min, which can maintain fuel temperatures above 0° F for all cases. Weight increases per airplane for these systems are estimated as 600 to 1000 pounds. Fuel consumption penalties for energy diverted to fuel heating are least for the tailpipe heat exchanger, 0.1 percent of the cruise fuel flow rate, and greatest for compressor air bleed, 3.9 percent. On the other hand, the tailpipe heat exchanger is perhaps the furthest from the state of the art in development feasibility; the compressor air bleed heat exchanger is the most practical concept. Table XI-1 includes two other items. Insulation, which holds great promise of reducing heating requirements, has a serious drawback in system weight and corresponding fuel consumption penalty. Reduction in heating requirements, as shown in figure XI-28, would not be sufficient to compensate for the insulation weight. Future designs, however, with composite wing material may incorporate lightweight insulation in the basic designs. Finally, the chart shows the equivalent fuel consumption representing 6200 Btu/min of combustion energy, about 80 lb/hr, or 0.4 percent of the cruise fuel flow. Systems that use heat rejection otherwise unavailable in the engine thermodynamic cycle, such as the tailpipe heat exchanger or some minor modifications, can have lower fuel consumption penalties than this combustion equivalent.

CONCLUDING REMARKS

The advantages and disadvantages of the various solutions to the problem of alternative fuels are summarized in table XI-2. The first solution is to continue to develop the necessary technology at the refinery to produce specification jet fuels regardless of the crude source. By this approach, the fuel properties may be optimized or tailored to the needs of future jet aircraft. Furthermore, this would eliminate the serious cost penalty of retrofitting existing aircraft and engines. The disadvantage of this approach would be increased energy consumption at the refinery and thus increased fuel cost.

The sensitivity of fuel costs is illustrated by the fact that a likely increase of 10 to 20 cents per gallon for hydrotreating to produce specification jet fuel from alternative sources would cost the commercial airlines an additional \$1 to \$2 billion per year.

The second solution shown in table XI-2 is to minimize energy consumption at the refinery and keep fuel costs down by relaxing specifications. The disadvantage of this approach is that more complex component technology must be developed to cope with the problems of increased pollutant emissions, increased combustor liner temperatures, poorer thermal stability, poorer ignition characteristics, and restricted fuel pumpability. Furthermore, using relaxed-specification fuels may adversely affect engine life, thereby reducing the time between overhauls.

Ultimately, the solution to these problems will involve determining the most energy-efficient and cost-effective path. The most practical solution will probably require a compromise between partially relaxing fuel specifications and a limited redesign of the aircraft and engine. The point of compromise will depend on the progress made in evolving the necessary refinery and aircraft engine technology.

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COMPARISON OF POSSIBLE FUEL HEAT SOURCES

	MAX HTG RATE/TANK, Btu/min	WT INCREASE, lb	FUEL PENALTY, %
AIR CONDITIONING SYSTEM	2100	LOW	0
LUBE OIL HEAT EXCH'R	4300	LOW	LOW
FUEL BOOST PUMP RECIRC'N	2000	LOW	LOW
COMPRESSOR AIR BLEED	6200	700	3.9
ENGINE-DRIVE ELECTRIC HTR	6200	1 000	1.1
TAIL-PIPE HEAT EXCHANGER	6200	600	.1
INSULATION - 1-in. THICK	----	13 000	14.6
EQUIV'T HEATING BY COMBUST'N	6200	-----	.4

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Table XI-1.

ASSESSMENT OF POTENTIAL SOLUTIONS TO JET FUEL PROBLEMS

SOLUTION	ADVANTAGES	DISADVANTAGES
PRODUCE SPECIFICATION JET FUEL	OPTIMIZED FUEL PROPERTIES AIRCRAFT/ENGINE RETROFIT NOT REQUIRED	INCREASED REFINERY ENERGY CONSUMPTION INCREASED FUEL COST
RELAX JET FUEL SPECIFICATION	CONSERVATION OF ENERGY REDUCED FUEL COST	MORE COMPLEX COMPONENT TECH REQUIRED ADVERSE EFFECT ON ENGINE LIFE

CS-77-581

Table XI-2.

U.S. AIR TRANSPORTATION FUEL CONSUMPTION ESTIMATES FOR CERTIFIED AIRLINES

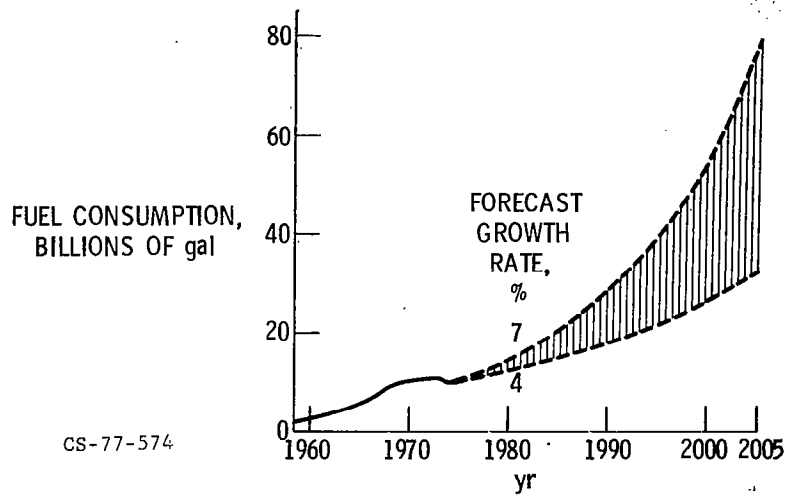


Figure XI-1.

COMPARISON OF U. S. RESOURCES

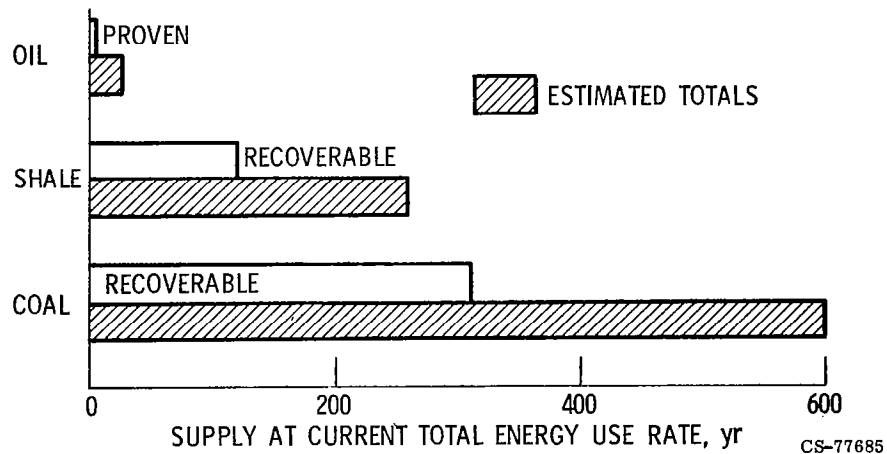
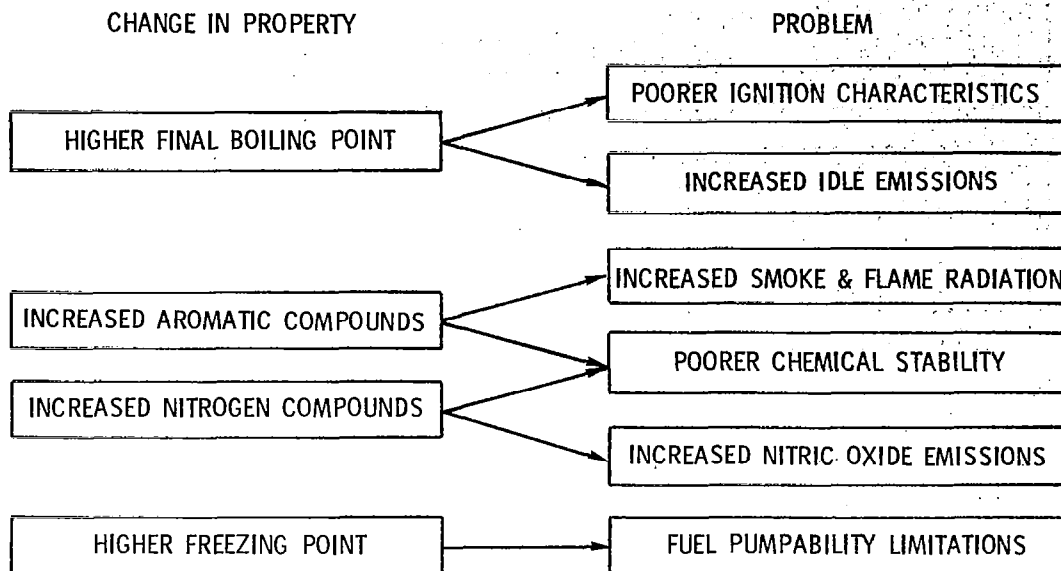


Figure XI-2.

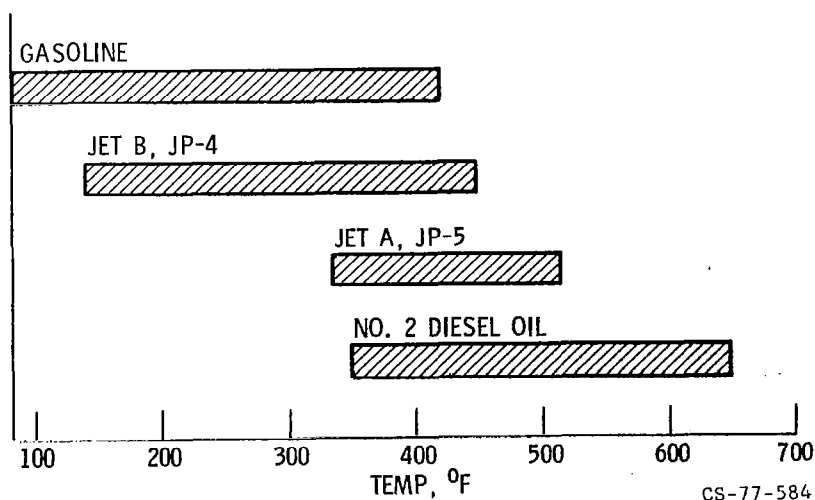
POTENTIAL PROBLEMS FROM RELAXING JET FUEL SPECIFICATIONS



CS-77-595

Figure XI-3.

BOILING RANGE OF VARIOUS PETROLEUM PRODUCTS



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Figure XI-4.

TYPICAL FUEL BLEND FREEZING POINTS

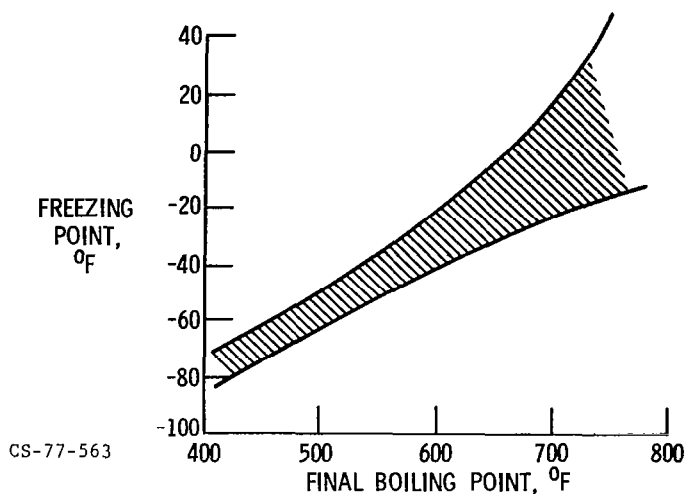


Figure XI-5.

AROMATIC COMPOUNDS

		H, wt %
BENZENE	$ \begin{array}{c} \text{H} \\ \\ \text{C} \\ // \quad \backslash \\ \text{HC} \quad \text{CH} \\ \quad \quad \\ \text{HC} \quad \text{CH} \\ \backslash \quad / \\ \text{C} \\ \\ \text{H} \end{array} $	7.74
ETHYL-BENZENE	$ \begin{array}{c} \text{H} \\ \\ \text{C} \\ // \quad \backslash \\ \text{HC} \quad \text{C}-\text{C}-\text{CH}_3 \\ \quad \quad \quad \quad \\ \text{HC} \quad \text{CH} \quad \text{H} \quad \text{H} \\ \backslash \quad / \\ \text{C} \\ \\ \text{H} \end{array} $	8.63
TETRALIN	$ \begin{array}{c} \text{H} \quad \quad \text{H} \\ \quad \quad \\ \text{C} \quad \quad \text{C} \\ // \quad \backslash \quad // \quad \backslash \\ \text{HCH} \quad \text{H} \quad \text{CH} \quad \text{CH} \\ \quad \quad \quad \quad \\ \text{HCH} \quad \text{H} \quad \text{CH} \quad \text{CH} \\ \backslash \quad / \quad \backslash \quad / \\ \text{C} \quad \quad \text{C} \\ \quad \quad \\ \text{H} \quad \quad \text{H} \end{array} $	9.15

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Figure XI-6.

VARIATION OF HYDROGEN CONTENT WITH AROMATICS CONTENT

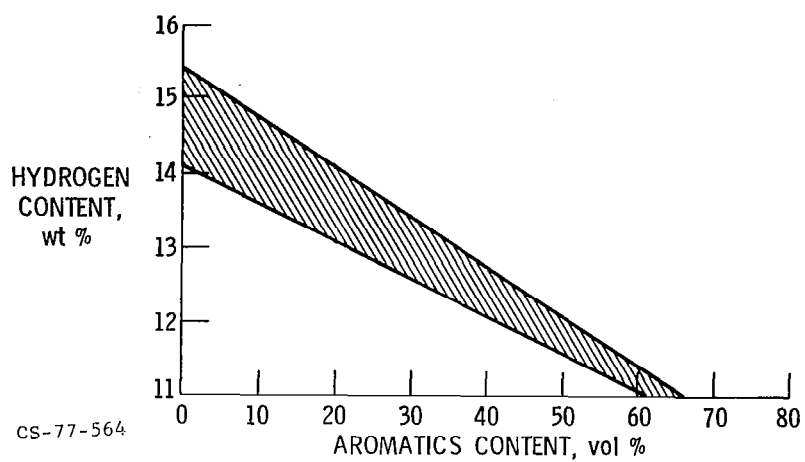


Figure XI-7.

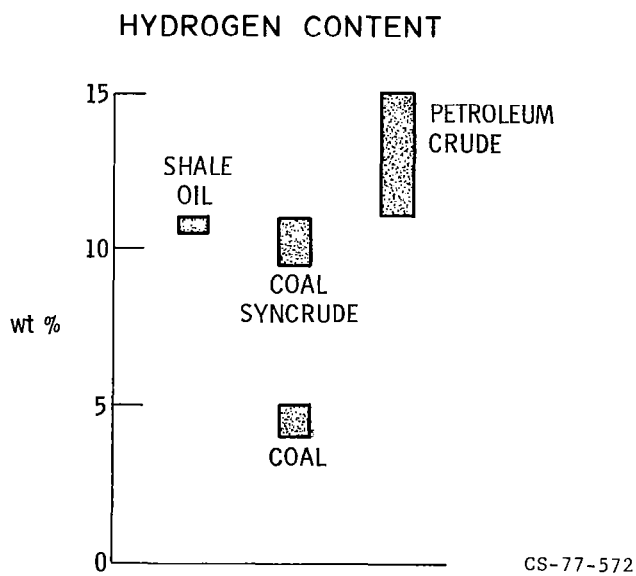


Figure XI-8.

NITROGEN CONTENT

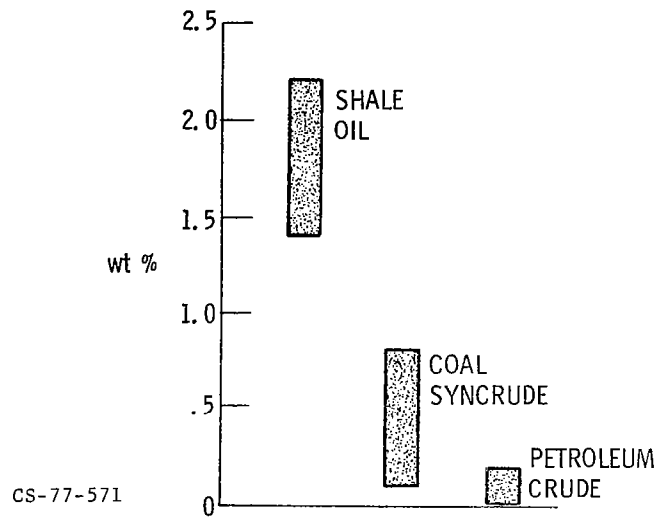


Figure XI-9.

EFFECT OF HYDROGEN CONTENT OF FUEL ON SAE SMOKE NUMBER

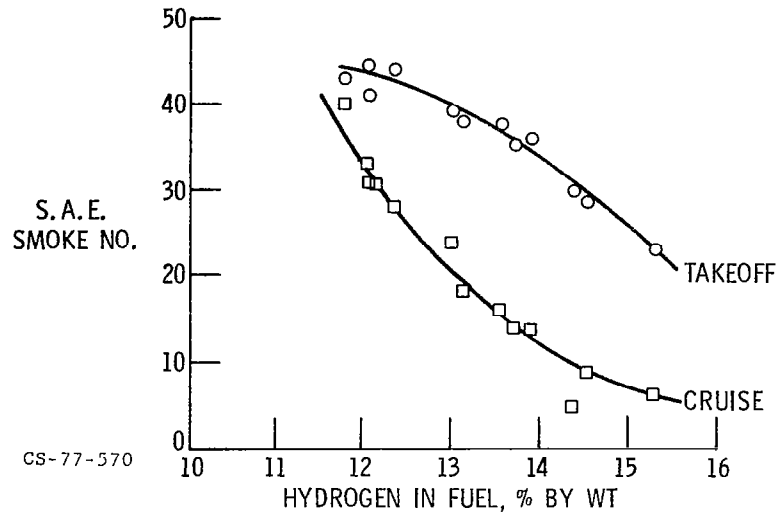


Figure XI-10.

EFFECT OF HYDROGEN CONTENT OF FUEL ON MAXIMUM LINER TEMPERATURES

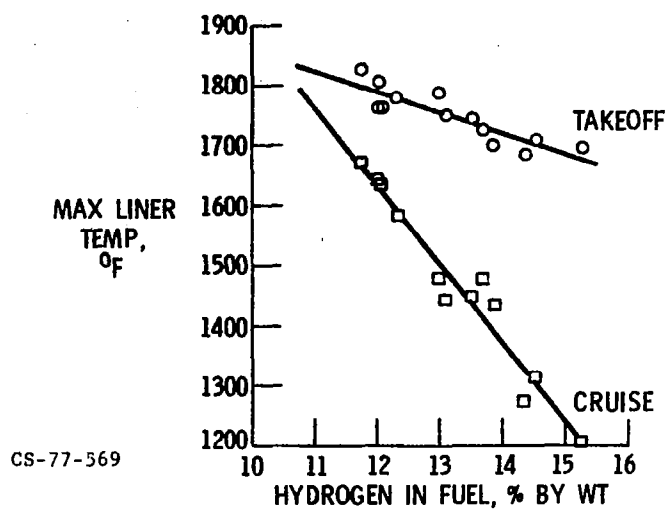


Figure XI-11.

EFFECT OF FUEL-BOUND NITROGEN ON EMISSIONS OF NO_x

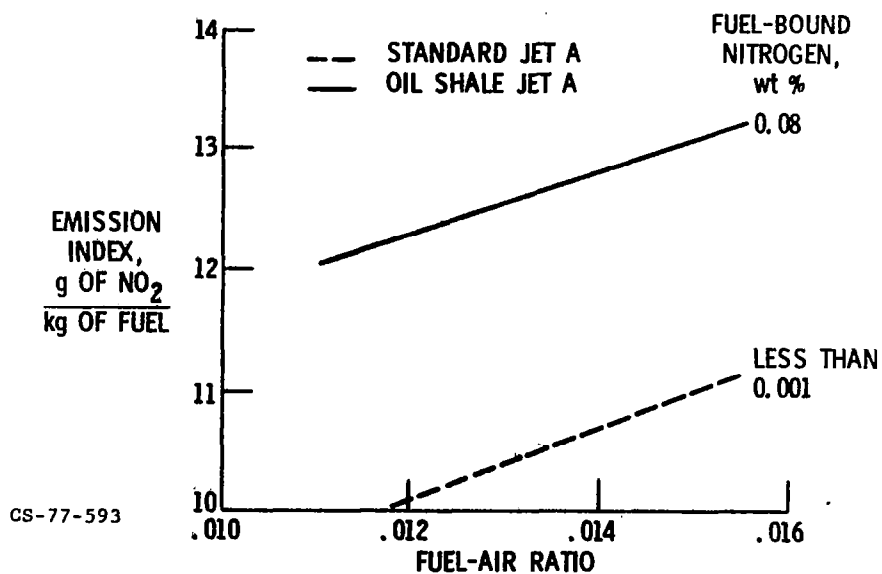


Figure XI-12.

THERMAL STABILITY OF SHALE FUELS

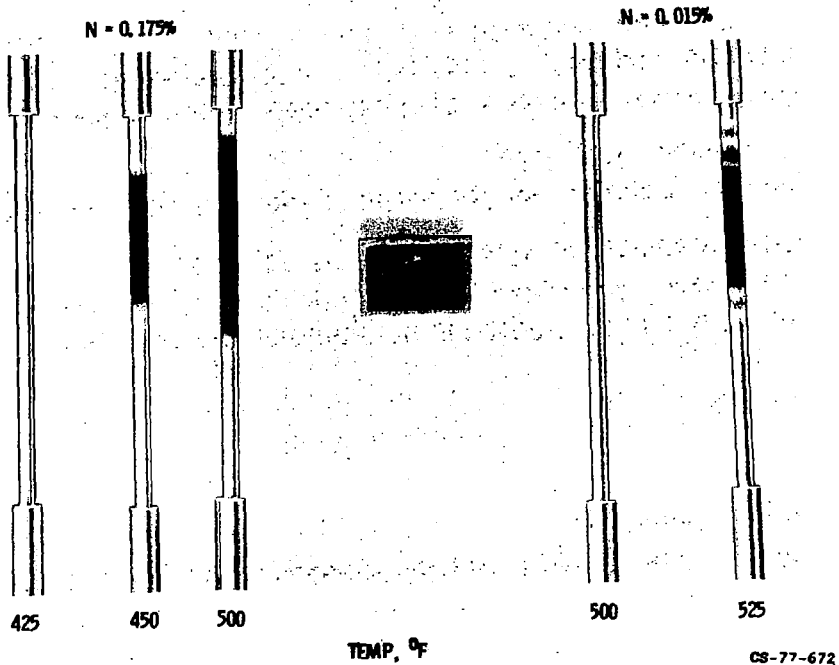


Figure XI-13.

FUEL TANK TEMPERATURES FOR 5000 N.M. FLIGHT

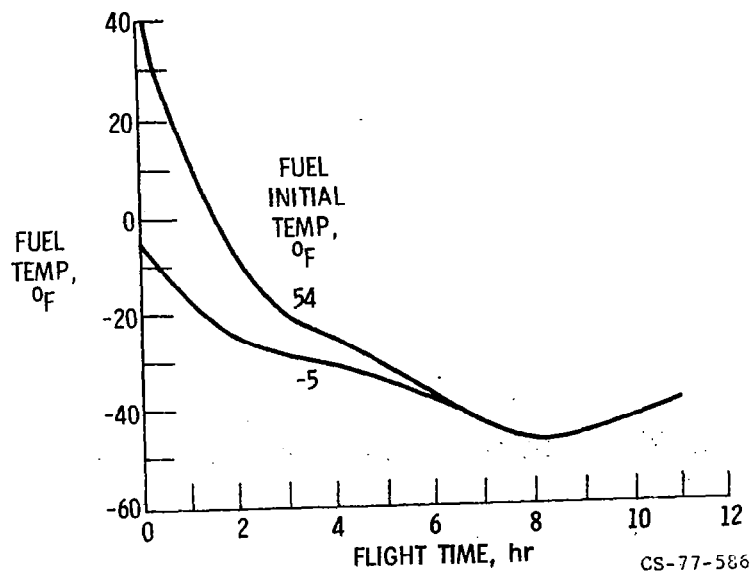


Figure XI-14.

SCREEN BLOCKAGE BY SEMISOLID FUEL- 707

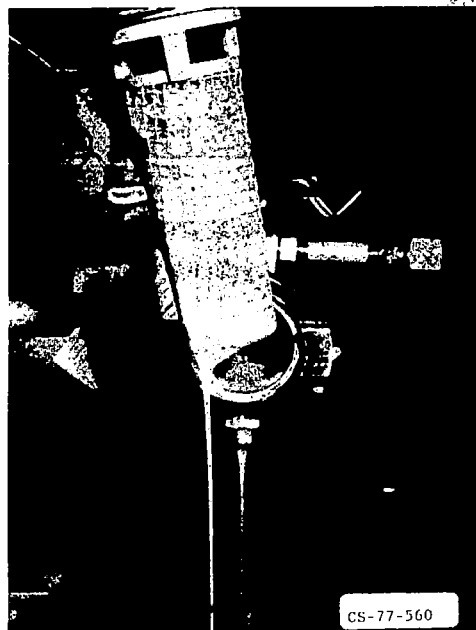


Figure XI-15.

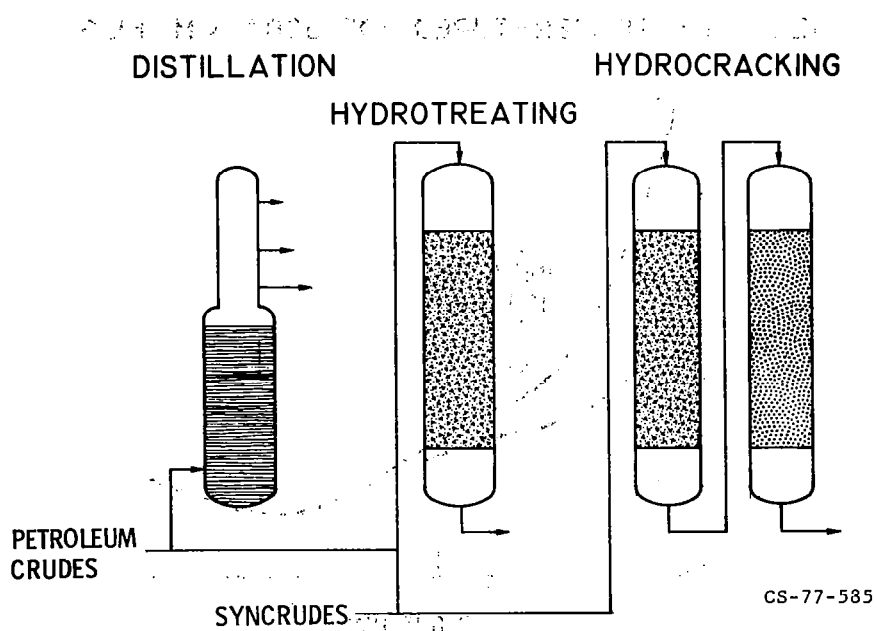


Figure XI-16.

HYDROGEN CONSUMPTION IN PROCESSING

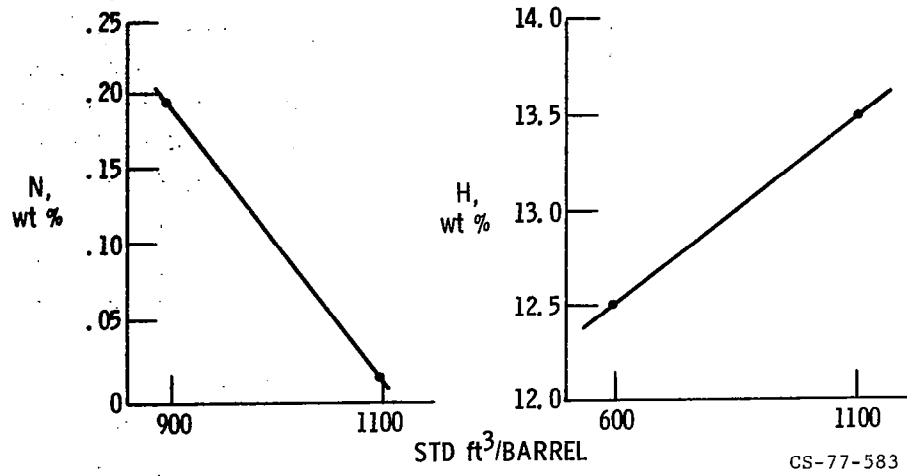


Figure XI-17.

THERMAL STABILITY TEST RIG SCHEMATIC

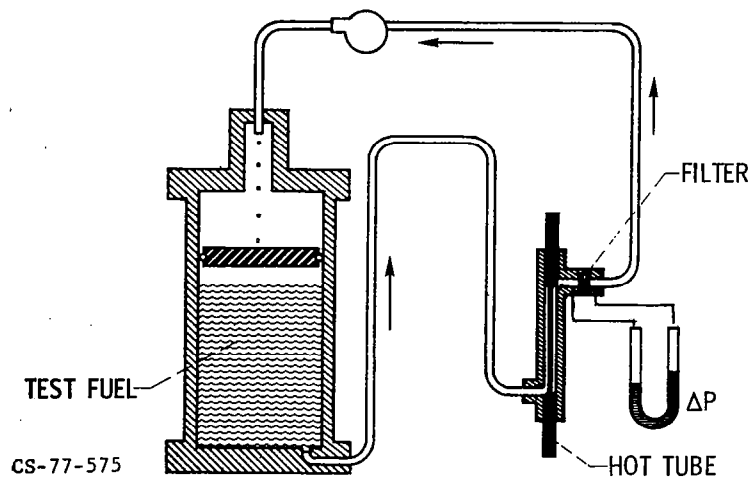


Figure XI-18.

BREAKPOINT TEMPERATURE DETERMINATION

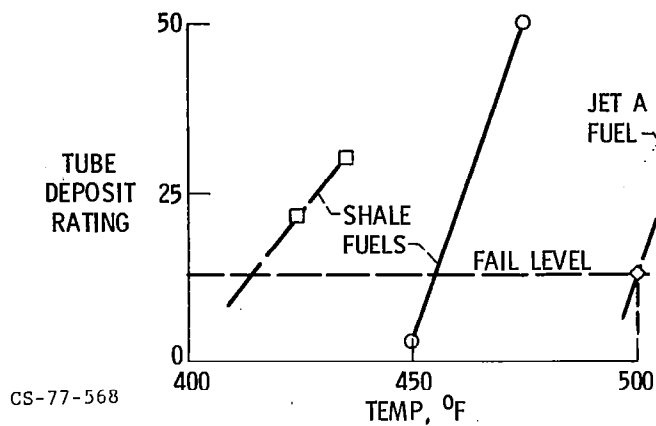


Figure XI-19.

VARIATION OF BREAKPOINT TEMP. WITH NITROGEN LEVEL

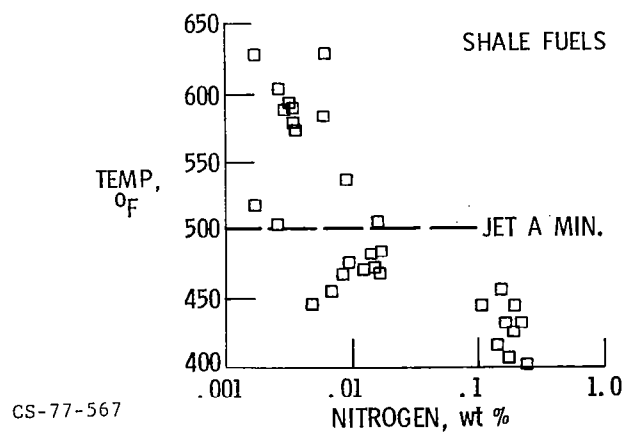


Figure XI-20.

VARIATION OF BREAKPOINT TEMPERATURE WITH HYDROGEN LEVEL

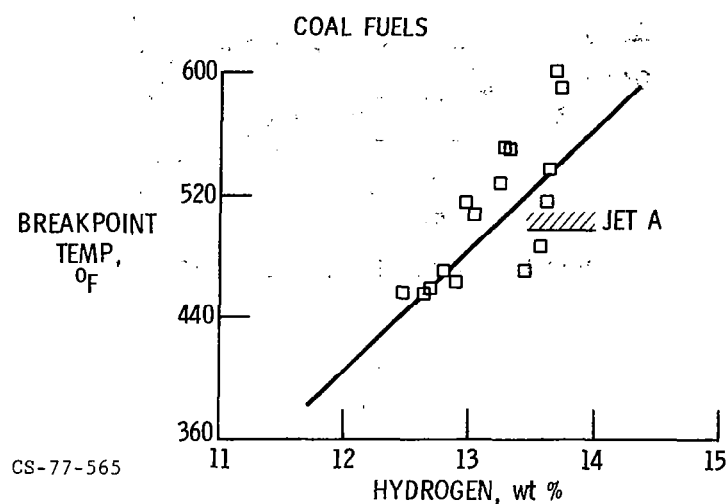


Figure XI-21.

VARIATION OF THERMAL STABILITY WITH FINAL BOILING POINT

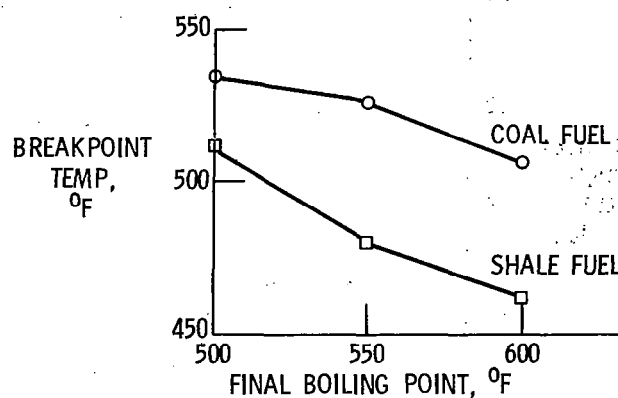
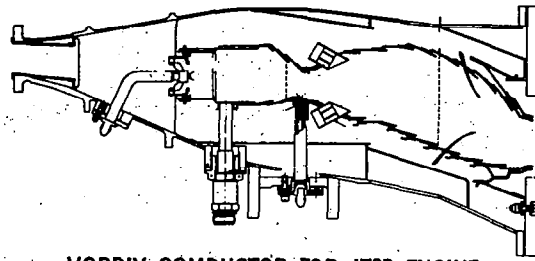
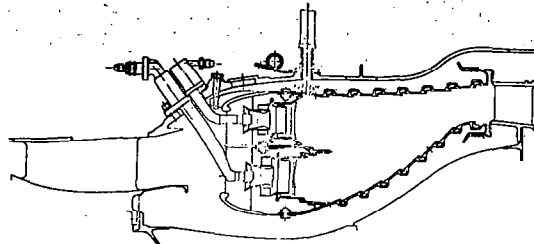


Figure XI-22.

COMBUSTOR DESIGNS FROM EXPERIMENTAL
CLEAN COMBUSTOR PROGRAM



VORBIX COMBUSTOR FOR JT9D ENGINE



DOUBLE-ANNULAR COMBUSTOR FOR CF6-50 ENGINE

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Figure XI-23.

EFFECT OF HYDROGEN CONTENT OF FUEL ON
COMBUSTOR LINER SURFACE TEMPERATURE

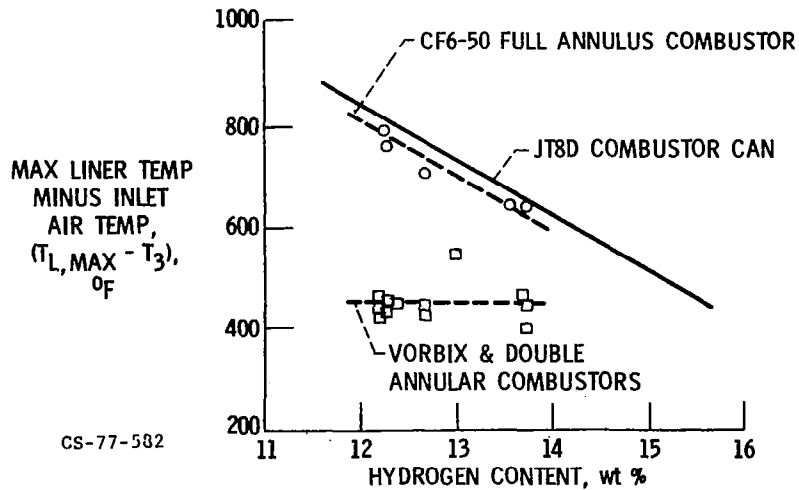
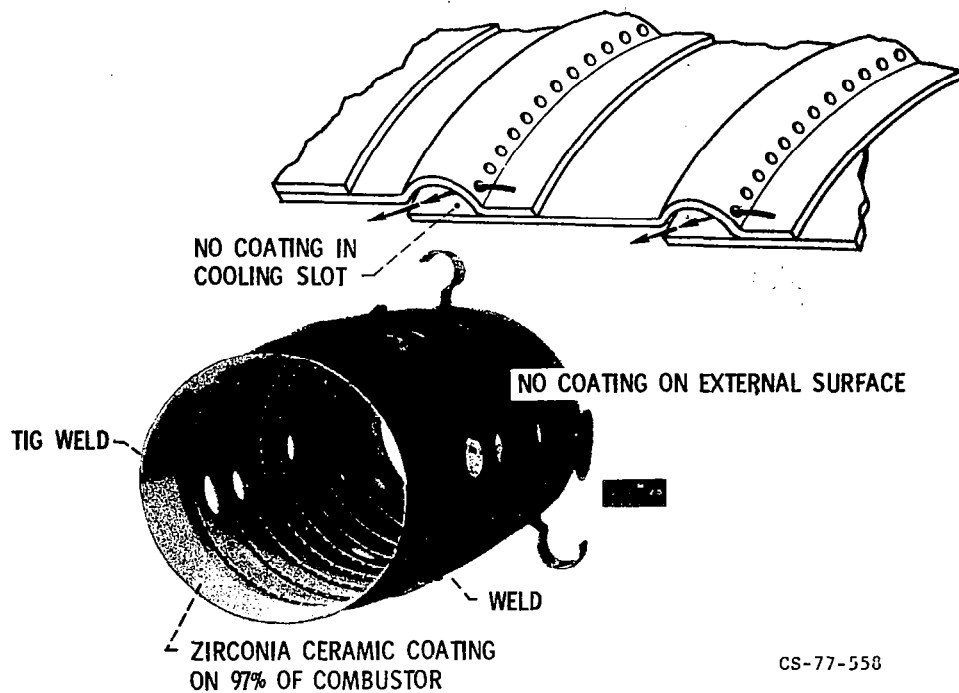


Figure XI-24.

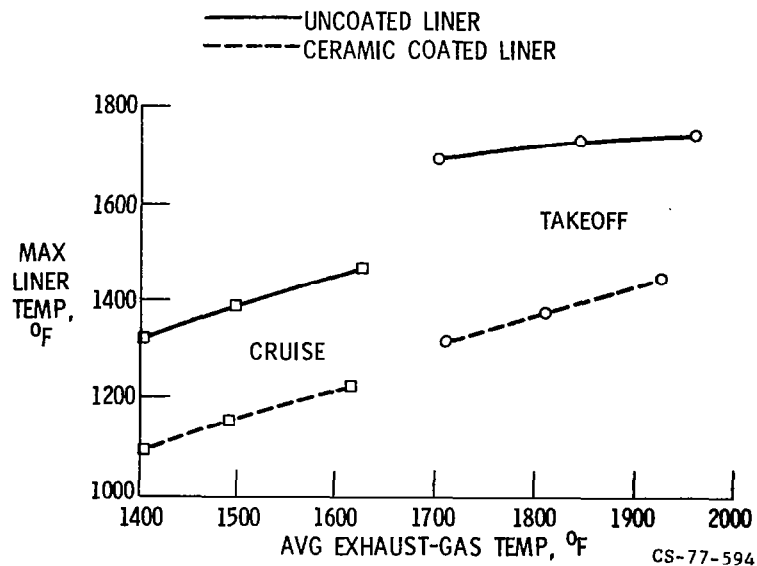
THERMAL BARRIER COATED COMBUSTOR



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Figure XI-25.

EFFECT OF CERAMIC COATING ON MAXIMUM LINER TEMPERATURE



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Figure XI-26.

FUEL TANK TEMPERATURES FOR 5000 N.M. FLIGHT WITH HEATING

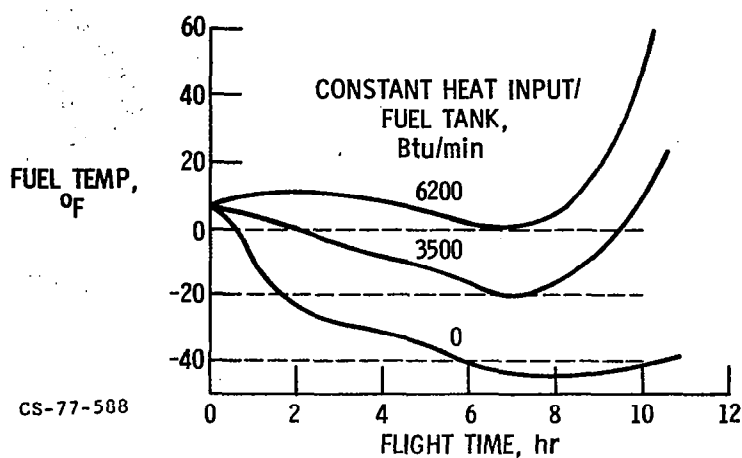


Figure XI-27.

REDUCTION OF FUEL HEATING REQUIREMENTS BY TANK INSULATION

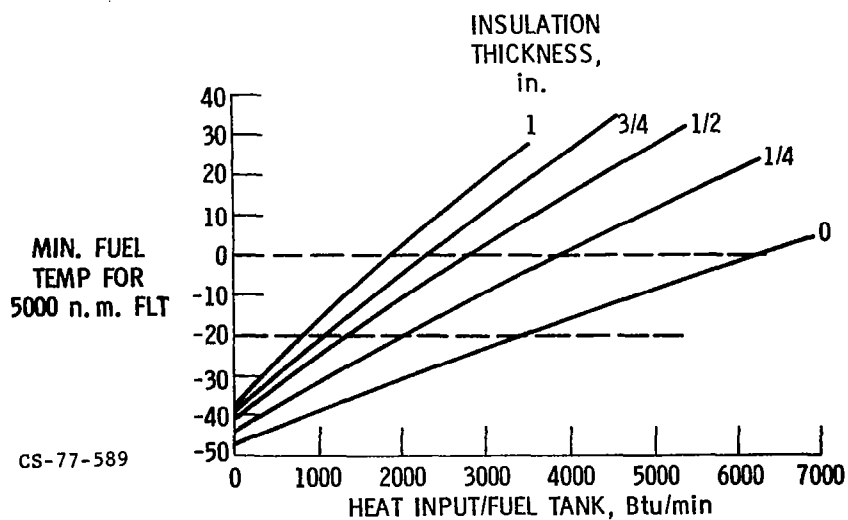


Figure XI-28.

FUEL TANK HEATING SOURCES

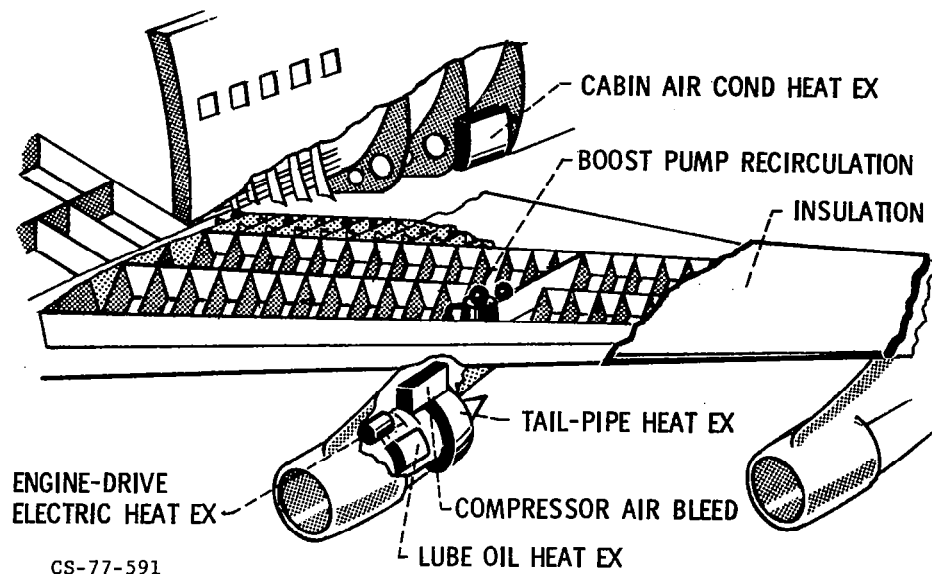


Figure XI-29.